The long term evolution of vertically-related industries*.

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Abstract

The paper develops the argument that the long-term evolution of an industry depends on the evolution of a vertically-related, downstream industry. We analyse two pairs of vertically-related industries, the jet and turboprop aircraft and engine industries, since the first introduction of the jet and turboprop technologies to 1998. The paper shows that the evolutionary dynamics of the downstream industry, in terms of number of firms and products, entry, exit and concentration, is transmitted to the upstream industry via the structure of the *network* of vertical relations. We identify two network configurations, *partitioned and hierarchical*, and show that they are responsible for sharply different transmission effects. A correlation analysis is carried out to demonstrate this difference in the turboprop and turbojet markets.

JEL classification: L13, L19, L22, L62

Key words: vertically-related industries; network; industrial concentration; entry; exit.

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1. Introduction

This paper develops the argument that the long term evolution of an industry depends in predictable ways, under some conditions, on the evolution of a vertically-related, downstream industry. More precisely, the evolutionary dynamics of the downstream industry, in terms of number of firms and products, entry, exit and concentration, is transmitted to the upstream industry via the structure of the network of vertical relations.

Depending on technology and market factors, the network may assume different configurations over time. We identify two basic configurations, partitioned and hierarchical, and show how different network configurations are responsible for sharply different transmission effects from one industry to the other.

We analyse two pairs of vertically-related industries, the commercial jet aircraft and engine industries, and the commercial turboprop aircraft and engine industries, since the first introduction of the jet (1958) and turboprop (1948) technologies to 1998. The evolution of these industries exhibits interesting characteristics concerning the number of competitors, the level of concentration and the competitive dynamics between incumbents and entrants. In the engine industry, the divergence of technological trajectories in propulsion technologies (turbojet and turboprop) originated markedly different market applications (large commercial aircraft and aircraft for regional transport) and led to the birth of independent segments of the industry. Turboprop and jet engine industries exhibit different structural dynamics with respect to the pattern of entry and exit of firms and products and the level of industry concentration. These differences can be explained by looking at the evolution of the downstream industry, but the transmission of effects from one industry to the other is filtered by the structure of the network linking the two.

The paper is organised as follows. Section 2 briefly presents several strands of relevant literature. Section 3 provides a detailed description of the long term evolution of each pair of industries. Section 4 develops the notion of network and gives detailed measures of the two networks for each year of the industry history, providing an original approach for the analysis of the dynamics of vertically-related industries. Finally, section 5 shows how network configurations are responsible for different transmission mechanisms in the two pairs of industries.

2. Background literature

The idea that the evolution of the industry may crucially depend on what happens to a vertically-related, downstream industry has been repeatedly proposed in industrial organisation. The earliest formulation of this idea was proposed by J.K. Galbraith with the notion of countervailing power (Galbraith, 1952). It was subsequently placed by Bain (1968) and Scherer (1980) within the structure-conduct-performance paradigm (see also Scherer and Ross, 1990), and recently reprised by von Ungern-Sternberg (1996) and Dobson and Waterson (1997). The main purpose in revisiting the theory of countervailing power is the analysis of the effects of bilateral oligopoly on the price for the buyer industry and for the final consumer. Although appealing, the notion is quite reductive: it is argued that concentration in a downstream industry is followed by parallel processes of concentration in the upstream industry. No implications are drawn on the specific mechanisms of transmission; other parameters of industrial dynamics such as number of firms and products, entry and exit are simply not considered. However, an increase in concentration is the outcome of a variety of processes: incumbent suppliers may survive but face a redistribution of their market shares, or may merge, or there may be exit of less efficient suppliers. Furthermore, there is scarce and contradictory empirical support to the notion (Lustgarten, 1975; LaFrance, 1979; Ravescraft, 1983).

In a different context, a large stream of literature in industrial organisation deals with sourcing decisions. The starting point of this research is the analysis of procurement decisions in the public sector, particularly in defence, with the purpose of designing optimal procurement schemes under imperfect information.

Rogerson (1994) summarises specific features of the defence acquisition process, which affect the decision for dual or sole sourcing: competition of suppliers is desired in the design phase but, given small quantities and discontinuous demand, only one source is selected because buying a defence system from a single supplier allows economies of scale in production. Important issues for government are also the choice of the sourcing solution which gives the right incentives to invest in innovation and in efficient production, and the possibility of monitoring suppliers' innovative efforts under asymmetric information and uncertainty about technology. A number of theoretical studies have tried to understand the real advantages of single or dual sourcing strategies (Demsky et al., 1987; Riordan and Sappington, 1989; Anton and Yao, 1987, 1989, 1992). Lyon (1996) empirically confirmed the hypothesis of negative effects of dual sourcing.

In summary, this literature provides elements for understanding the costs and benefits of isolated procurement decisions. Understanding the effects of a sequence of decisions regarding multiple products in a dynamic context is beyond its scope, and the implications of sourcing strategies for the structural dynamics of supplier and buyer industries are not addressed.

Existing theories of industrial dynamics posit a direct relation between attributes of technological regimes and stylised dynamic properties of the structural evolution of the industry. Recent contributions of industrial demography and industrial dynamics (Geroski, 1994; Audretsch, 1995; Baldwin, 1995) discuss the set of variables for the analysis of industry structure and of the dynamics of populations of firms: birth and death rate and density of the population, level of industry concentration, firm size distribution, patterns of growth of individual firms, dynamics of market shares. Attributes of technological regimes include the level of technological opportunities, cumulativeness of knowledge, and appropriability regime (Nelson and Winter, 1982; Malerba and Orsenigo, 1993, 1996a). Developments in the modelling of industrial dynamics provide a clear analysis of the relationship between technological regimes, evolution of market demand, and structural evolution of the industry (Dosi et al., 1995, 1997; Malerba et al., 1997; Winter et al., 1997, 1999).

Recently, in different industries, patterns of vertical integration and disintegration, and division of labour have been observed as relevant engines of changes of industry structures. In the chemical industry the emergence of specialised engineering firms represents an example of the economies of specialisation and division of labour at the industry level, which enormously affected the evolution of the industry structure, through entry of new firms and intensification of the competition (Arora and Gambardella, 1998). In the computer industry (Bresnahan and Malerba, 1999; Bresnahan and Greenstein, 1999) and in the semiconductor industry (Langlois and Steinmueller, 1999) the emergence of standards and platforms stimulated entry and growth of specialised suppliers of components. In these industries, the changing patterns of vertical integration / disintegration strongly influenced the dynamics of competition.

One very recent frontier in evolutionary modelling of industrial dynamics is the explicit consideration of the joint dynamics of two vertically-related sectors. Malerba et al. (1998) developed a 'history friendly' model of the dynamics of vertical integration and disintegration occurring in the computer industry as the result of the dynamics of capability and upstream and downstream market structure, the latter being represented by the presence of a dominant leader which can exploit static and dynamic increasing returns from specialisation or vertical integration.

In his recent major work, John Sutton discusses the notion of interdependence of sub-markets (Sutton, 1998). The extent to which industries are concentrated is limited by the degree of interdependence between markets that address specific needs or use particular technologies within the same industry. Sutton predicts that in industries with high interdependence of sub-markets the lower bound to concentration is high, while industries with fragmented sub-markets exhibit a variety of outcomes, some of which may be characterised by low concentration.

In sum, although the need of including the vertical structure in the analysis of long term evolution of industries is clearly recognised, much work must still be done.

We develop an original approach which is based on a construct, the network of vertical relations between individual firms in buyer and supplier industries, which is used to explain the evolution of vertically-related industries. The formation and evolution of the network is explained through various characteristics of vertical relations which are drawn from contributions in industrial organisation and evolutionary economics.

There are a number of advantages originating from the use of a network approach to study the coevolution of vertically related industries. First, the unit of analysis is the single transaction, but it is not isolated from all other transactions taking place in the industry. As Holmstrom and Robert (1998) pointed out, “in market networks, interdependencies are more than bilateral, and how one organises one set of transactions depends on how the other transactions are set up”. Second, specific factors featuring vertical relations such as presence of asset specificity, technological complementarities, frequency of relations, or pattern of sourcing, are carefully reflected in several network measures at the transaction level, at the firm level (buyer and supplier), and at the overall network level. For example, the adoption of single or multiple sourcing strategies is represented by the number of relations for buyers. Diffuse adoption of multiple sourcing leads to a dense network, while single sourcing shapes a less dense network, which is also partitioned if the supplier industry is not monopolistic. Third, the relationship between the dynamics of vertical relations and industrial dynamics can be studied through the analysis of the relationship between variables describing upstream and downstream industries, i.e. level of concentration, dynamics of market shares, entry and exit, and variables describing the network.

This paper analyses a particular case of vertically-related industries, i.e. a supplier industry which sells only to one downstream industry, which in turn cannot substitute the products with those of competing sectors. The two industries are strictly intertwined. There is no diversification, either in market demand for the upstream industry, or in supply sources for the downstream one. Of course, there is still the possibility that the survival of firms is subsidised by military sales or government interventions. Although this applies to specific circumstances, it is difficult to accept as an explanation of long term evolution[1].

This is an ideal case for discussing the coevolution of two industries, since external influences are ruled out. In some sense, we are dealing with a quasi laboratory experimentation.

In addition, we are able to push the analysis of vertical structure to the finest level of detail, namely transactions between individual customers and suppliers over the entire history of the industry.

3. The long term evolution of the turboprop and jet industries

This section describes the evolution of number of firms, entry and exit, industrial concentration and introduction of products in the jet and turboprop engine and aircraft industries. Information about data used in the empirical analysis are reported in the Appendix. We analyse separately the jet and turboprop industries, by looking at the relation between industrial dynamics in buyer and supplier industries. In other words, we emphasise the impact of the dynamics of each variable in the aircraft industry on the dynamics of the same variable in the engine industry.

Aircraft and engine industries, in both jet and turboprop, are characterised by a stable pattern of vertical separation, that is, vertical integration of engine production never occurred over the entire history of these industries.

3.1 A brief history

The propeller-piston engine combination was the prominent aircraft propulsion system until the Second World War. Military needs to operate at higher altitude and speed induced the search for alternative forms of propulsion systems, which did result in the affirmation of two propulsion systems: *turboprop* and *turbojet* (Constant, 1980). Each propulsion system was

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[1] Although economies of scope are clearly relevant in R&D, commercial engines are developed for being integrated into commercial aircraft, with no easy cross-over with military products.

designed for specific ranges of operating conditions (aircraft speed, altitude, air density and temperature, passenger capacity). Military needs for turboprop were less pressing, because of the higher performances promised by the turbojet technology, but the turboprop was of more immediate interest to the airlines than the jet (Miller and Sawers, 1968).

The 1950s represented a transition period for the airliners, as air carriers adopted the jet or turboprop engined designs for some operations, but continued to buy piston engines for others (*Flight International*, 1999a). The turbojet engine was more efficient than a piston propeller engine at speeds over about 450 m.p.h. (Miller and Sawers, 1968). At medium speed and altitudes the turboprop was generally more efficient than a pure turbojet. This period was characterised by high uncertainty about the cost performances of jet and prop technologies and by intense competition between the two systems.

Competition between jet and prop occurred especially in the segment of aircraft with 51-90 seats. Over time, the markets with smaller seat capacity have been dominated by the turboprops, while the markets with larger seat capacity (91-120 to more than 400 seats) by the jet. As shown by figure 1, the size of the market for jet was substantially larger than the turboprop. The evolution of the market has been characterised by several peaks. The birth of the prop industry is characterised by a continuous and rapid growth until the peak in 1959. After the introduction of the jet, which witnessed a tremendous growth until 1968, the demand for turboprop engines sharply decreased and stayed at low levels, with some oscillations, until the 1980s. The deregulation in the airline industry, more than any other factor, created the market for new turboprops. This has stimulated the development of new technologies for turboprop engines and aircraft, the introduction of many new programs and the entry of new actors (Aerospatiale, 1989; Airbus Industrie, 1991; FAA Forecasts and Technology Plans, 1994). As shown in Figure 1, after 1978 the market for turboprop engines was characterised by remarkable rates of growth. The production of engines more than doubled in the 10 years following the deregulation.

During the 1990s the regional aircraft market has undergone a new radical change. The market has shifted, this time irreversibly, from turboprop to turbofan, and supply of turboprops has currently to face a dramatically reduced demand (Schaffler, 1991; U.S. International Trade Commission, 1998; *Flight International*, 1997a,b; 1998a,b; 1999b). The process of technological substitution is leading to a structural decline of the turboprop industry, characterised by a reduction of orders, a process of riconversion to the jet technology undertaken by turboprop aircraft manufacturers, the birth of joint development programs among turboprop aircraft manufacturers (*Flight International*, 1997c; 1998c; 1999c), and the exit of some airframe producers.

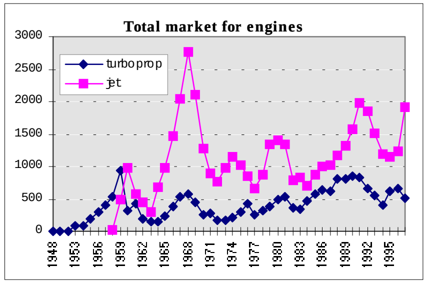

Figure 1. Evolution of markets for turboprop and jet engines

3.2 Entry, exit and number of firms

Turboprop market

The turboprop engine industry is composed of a small number of players, while the number of aircraft manufacturers is higher. Since their birth, the engine industry has counted 9 engine manufacturers while the aircraft industry 22. Figures 2a and 2c show the evolution of the number of firms and the process of entry and exit. The peak number of firms competing at the same time is 7 in the engine industry and 14 in the aircraft industry, and this occurred during the 1980s, when the turboprops registered high rates of development. The two industries did not experience a shakeout during their evolution, although several companies have been exiting the industry in the last decade. The reduction in the number of players can be considered a part of the process of progressive disappearance of the industry, due to technological substitution by the jet.

It is interesting to analyse the relation between entry and exit of aircraft and engine manufacturers. The history of each entry and exit event highlights some stylised facts.

1) New aircraft manufacturers are either served by existing or new suppliers.

2) Entry of suppliers always occurs to serve new customers. After the first flight of the Vickers Viscount in 1948 and of the Fokker F27 in 1955, powered by the Rolls Royce Dart, in 1957 Allison enters to power the Lockheed L-188 Electra. In 1963 the aircraft manufacturer Nord Aviation enters the market, supplied by Turbomeca. In 1965 Pratt & Whitney and

General Electric supply two different aircraft programs introduced by the entrant de Havilland Canada. With the exception of Walter, which enters to substitute Pratt & Whitney for powering the Let 41, all the other engine manufacturers enter by supplying new entrants in the aircraft industry: Pilatus and Lycoming in 1973, Casa and Garrett in 1974, Yunshui and Dongan in 1984, IPTN and Allison in 1995.

3) New aircraft programs introduced by existing customers are generally powered by the established engine supplier, unless the new program is introduced in a different segment of the market which is not served by the existing supplier. Specialisation by market segments and absence of economies of scale and scope lead to a configuration of the industry in which engine suppliers operate mainly in just one segment of the market. In this industry context, although turboprop aircraft manufacturers operated mainly in single sourcing, the introduction of a program in a new market segment often required the establishment of a supply relation with a second source. An example is provided by Casa, which was supplied by Garrett in the less than 30-seat segments and by General Electric in the segment 31-50 seats.

4) Minor engine manufacturers are induced to leave the industry by the exit of their main customer. This is the case of Allison in 1969, Turbomeca in 1976, Walter in 1995 and Lycoming in 1996. Note that these firms were not owned by aircraft manufacturers but were independent, privately-hold companies. On the contrary Rolls Royce, the leader of the market for many years, progressively lost market shares and left the industry after the exit of its former customers. The last supply relation gained by Rolls Royce was Fairchild in 1968. After the financial crisis of the 1970s, Rolls Royce concentrated its efforts only in the jet market and did not introduce new products in the turboprop industry. This caused its exit from the market in 1988.

Jet market

The jet engine and aircraft industries are also composed of a small number of players. As in the turboprop, the number of players is higher in the aircraft than in the engine industry. Since their birth, the engine industry has counted 7 engine manufacturers while the aircraft industry 16 (Figures 2b and 2d). The peak number of firms is 7 in the engine industry and 9 in the aircraft industry. They occurred in different periods in the aircraft (1970s) and in the engine (1990s) industry. The jet engine industry did not experience a shakeout during their evolution, as no firms exited the industry. The aircraft industry experienced a reduction in the number of firms, which continued in 1998 with the exit of Fokker and the acquisition of Mc Donnell Douglas by Boeing. However, as evident from figure 2d, there is no clear evidence of shakeout as new firms are entering the small jet segment of the market.

With respect to the stylised facts observed in the turboprop, the jet presents sharp differences.

1) New aircraft manufacturers are always served by existing engine suppliers. The only exception is the entry of Embraer supplied by the new entrant Allison in the segment of the small regional jets.

2) Engine manufacturers do not enter to supply new, but existing aircraft manufacturers, except the case of Embraer and Allison mentioned above. Entry of suppliers is not fuelled by the entry of new customers or the launch of programs, but by the increasing adoption of multiple sourcing at the aircraft manufacturer and at the program level. Airbus, Boeing and Mc Donnell Douglas operated with three, and in some periods with four or five engine manufacturers. Starting from the B747, other programs such as the A330, the B767 and the B777 have been powered by engines of three different engine manufacturers. The affirmation of multiple sourcing strategies implies that the launch of a new program is an opportunity for more than one engine manufacturer, which compete to gain the launch order or a large share of total orders. However, a number of minor aircraft manufacturers operated in single sourcing, but they did not create opportunities for entry, as their aircraft have been powered by engines of existing suppliers, in most cases by Rolls Royce engines.

3) There is no established pattern for the choice of the engine supplying the launch of a program by an existing aircraft manufacturers. Obviously, companies operating in single sourcing powered new programs with their established suppliers, although most of them introduced just one program during their life. Companies operating in multiple sourcing used in some cases already involved suppliers, in other cases suppliers that, although active in the market, did not supply them before.

4) As no exit of engine manufacturers occurs during all the history, there is no relation with the exit of aircraft companies.

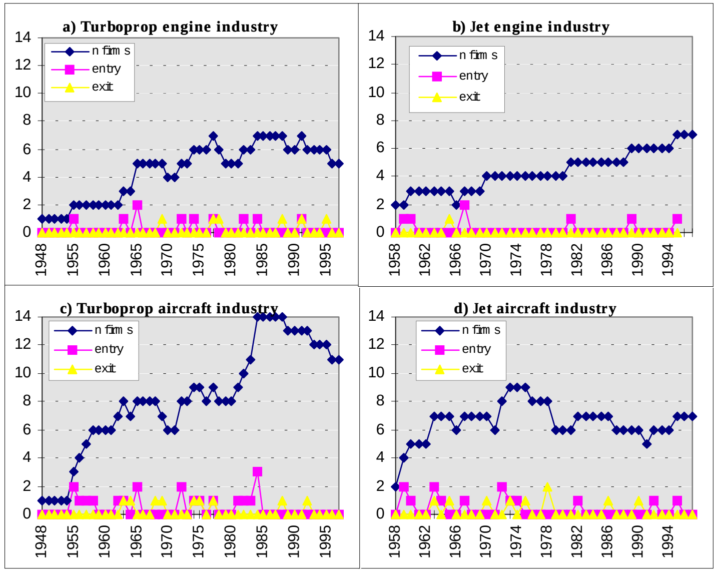

Figure 2. Number of firms, entry and exit

In synthesis, it seems interesting to observe that while the turboprop industries aircraft and engine industries followed a similar dynamics, the jet aircraft and engine industries experienced a different pattern of evolution.

3.3 Industrial concentration

Turboprop market

The level of industrial concentration during all the history analysed is clearly higher in the supplier than in the buyer industry (figures 3a and 3c).

In the engine industry, the CR2 index is very high over all the history. It is at its maximum value during the first years of the industry life, as there are only two firms. It starts to decrease for the entry of new firms, but at least the 70 % of the market is still dominated by two companies. The second half of the time series shows again an increasing trend. The same pattern is displayed by the Herfindahl index. The dynamics of market shares underlying the evolution of the level of concentration reveals that the market is always dominated by a strong leader. The former leader was Rolls Royce, which maintained its position until the end of the 1960s. As mentioned above, the leader progressively

decreased its efforts in the turboprop industry and lost market shares for the exit of its customers. The leadership was gained by Pratt & Whitney, entered in 1965, through the acquisition of several customers in the smaller seat-segment of the market, which witnessed a substantial growth during the 1960s and the 1970s and ended up to represent a large share of the total market. However, other companies in the market secured important shares in different market segments.

On the buyer side, the level of industrial concentration was remarkably lower. The turboprop aircraft industry is characterised by a low and decreasing level of concentration, and by the absence of a dominant leader in the total market and in each segment. Until the 1970s a few large companies owned large shares of the markets, and the two largest, de Havilland Canada and Embraer, dominated on average the 50 % of the market. The level of concentration rapidly decreased after the entry of new competitors, which eroded the positions of the incumbents in all market segments. The industry then became highly fragmented, and characterised by the complete lack of dominant players.

Jet market

The dynamics of concentration in the jet engine and aircraft industry is different from the prop. The jet engine industry shows a remarkable process of decreasing concentration, while the aircraft industry is characterised by a quite high and unstable level of concentration (Figures 3b and 3d).

In the first decade of the jet engine industry evolution two firms created a quasi stable duopolistic market structure, in which the first mover Pratt & Whitney had a pronounced leadership over the second player Rolls Royce. The level of concentration slightly decreased due to the subsequent entry of two large competitors (General Electric and Snecma), which rapidly gained significant market shares. During the 1980s industry concentration decreased very rapidly, and the leader was replaced by the entrant of the second phase General Electric. The final configuration of the industry was oligopolistic, characterised by strong instability of market shares and turbulence of the players' positions. The entry of minor companies, which acquired small shares of the market, contributed very slightly to the reduction of concentration. On the contrary, intense competition among the four larger companies for the same customers and products led to mobility of their market shares.

The jet aircraft industry has been characterised by the persistence of a strong leader, Boeing, for all the industry life. The CR2 index indicates that two companies dominated at least the 70 % of the market. The oscillation of the two indexes until the end of the 1970s are explained by entry of new firms, which tried to compete with Boeing and the follower Mc Donnel Douglas. The growth of the new entrant Airbus, which eroded the leader's market share, the exit of Lockheed and other minor companies, and the emergence of the market for small jets, initially dominated by new comers, explained the slow decline of the concentration. In 1998 the industry concentrated again, as Boeing acquired the competitor Mc Donnel Douglas and Fokker exited the industry.

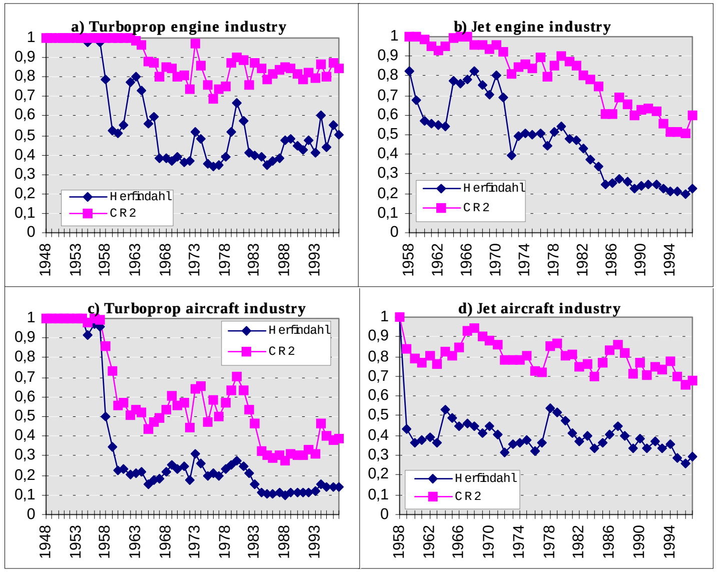

Figure 3. Level of industrial concentration

Comparing the engine and aircraft industries we may observe that, although the processes of concentration are different in the four industries, the dynamics of the two pairs of vertically-related industries are similar over time. In the turboprop they show simultaneous increasing and decreasing patterns, in the jet they show a decreasing pattern, but characterised by different competitive dynamics among major players.

3.4 Introduction of products

Figure 4 displays the evolution of the number of products and the introduction of new products in the four industries analysed.

The turboprop aircraft and engine industries shows a strong similarity in the patterns (Figures 4a and 4c). The number of products increases during the 1950s, shows a weak reduction due to the exit of the first models introduced and tend to stabilise until the 1980s. Then the number of products rapidly increases, following the growth of the market fuelled by the deregulation in the United States and in Europe.

The patterns in the jet engine and aircraft industries is clearly different. In the jet engine, the number of products grows almost monotonically, except a reduction during the 1990s, which reflects the substitution of many models of the second generation, introduced during the 1970s (Figure 4b). The number of aircraft increases at very high rates during the 1960s, than decreases and tend to stabilise during the 1980s and the 1990s (Figure 4d). The sharp growth and exit of products during the 1960s is explained by the introduction of a high number of different versions of the first programs introduced, the B707, DC-8 and DC-9, rapidly replaced by improved versions and new aircraft programs.

The analysis of the patterns of introduction of products in the two pairs of industries is explained by the following observations.

In the turboprop engine industry, more than 55 % of the engine versions are introduced to power a single aircraft program version. About 40 % of the engine versions power a few, in most cases two or three, versions of the same aircraft program. Only 5 engines power more than one aircraft program of different aircraft manufacturers in the same segment of the market. In the turboprop aircraft industry most of the aircraft, 109 out of 129, are powered by only one engine version, while a small number of aircraft integrate two versions of the same engine program.

In the jet engine industry we may observe three differentiated patterns.

A number of engines power only one aircraft version. This is the case of engines powering aircraft for specific markets (the Rolls Royce M45 which powered the VFW614 in the regional market, the Olympus 593 which powered the Concorde) and the case of the *last generation* engines, which are developed in many versions to power the same aircraft model, in order to satisfy the need of aircraft manufacturers to meet many specific requirements of airlines. Examples are a number of versions of the Trent, the PW 4000 series, the IA V2500 series. Different versions of these engines are integrated on the same aircraft version in order to obtain specific operating conditions.

Other engines are integrated in different models and versions of the same program.

Finally, several engines of the *first and second generation* are integrated in many versions and programs of different aircraft manufacturers. To name some examples, in the 1960s the Pratt & Whitney JT3D-3B has been integrated in 38 versions of the B707, B720 and DC-8, the JT8D-7 in 18 versions of the Caravelle, B727, B737 and DC-9, while in the 1980s and the 1990s the General Electric CF6-80C2 has powered 22 versions of the A300, A310, B747, B767 and MD-11.

An inverse pattern may be noticed in the aircraft industry. Many different versions of the *first generation* of aircraft (B707, B720, DC-8, DC-9 and Caravelle) have been powered by only one engine version. The same pattern was found for the regional aircraft (Fokker, BAe 146, Canadair Regional Jet).

Many aircraft of the *second generation* (B727, B737, B747, MD-80) integrated a number of versions of the same engine program, while the aircraft of the *third generation* (Airbus A300-600, A319, A320, A330, B757, B767, B777) are introduced in multiple sourcing. Each aircraft integrates different versions of programs of different aircraft manufacturers. As an example, each version of the B777 integrated several versions of General Electric, Pratt & Whitney and Rolls Royce engines.

In summary, the pattern observed in turboprop suggests the existence of close technological complementarity between engines and aircraft, which induces the introduction of new engine versions in correspondence with launch of new aircraft. In the jet, aircraft and engines of different generations are designed to operate in many seat-range conditions. Technological factors underlying the differences between jet and turboprop have been shown by Bonaccorsi and Giuri (1999a,b), which have provided evidence of the lack of economies of scale and scope in design and production activities in the turboprop, and of their existence in the jet.

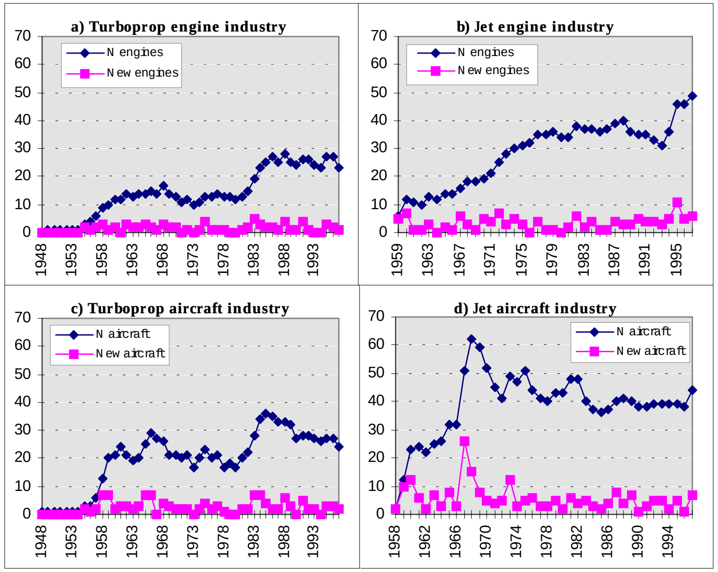

Figure 4. Total number of products and introduction of new products

4. The structure and dynamics of the network

In this section we analyse the evolution of the network of vertical relations between engine and aircraft manufacturers to highlight the structural differences between turboprop and jet industries.

For the analysis of vertically-related industries we study bipartite graphs, in which edges connect vertices from different sets of actors (buyers and suppliers) and there are no ties within each set (Borgatti and Everett, 1997; Asratian et al., 1999). The edges in the network are determined by the order of an engine placed by an aircraft company to an aero-engine manufacturer at a given date. The structure of the relations is represented for each year by a biadjacency matrix, whose cells represent the binary variable “a relation exists / does not exist”.

In related papers we used density as a synthetic measure of network structure and traced it over time. The *density* is essentially a count of the number of edges actually present in a graph, divided by the maximum possible number of edges in a graph of the same size. It provides information about the group relational intensity and the cohesion of a graph, but does not include information about the variability among actor degrees.

In this work we also calculate measures at the subgroup level, to obtain a more detailed representation of the structure and dynamics of vertical relations. In particular we study the number and size of *k*-cores and bi-components, which give a clear representation of the presence of cohesive sub-groups, and of the connectivity and separability of the network.

A *k*-core is a connected maximal induced sub-graph which has minimum degree greater than or equal to *k* (Wasserman and Faust, 1995). The degree of an actor is the number of edges incident with that vertex. Each member of a *k*-core relates with at least *k* other actors on the other set. We calculate the number of *k*-cores in the jet and turboprop networks for every possible value of *k* and for each year of their life. For *k*=1 the number of cores *n* indicates the degree of *partition* of a network, that is the network can be separated in *n* sub-graphs without deleting any vertex. The presence of cores with degree greater than or equal to *k* denotes connectivity of a graph. In particular, a network characterised by a restricted core and a periphery of disconnected actors can be defined *hierarchical*.

A bi-component (or block) of a graph is a maximally non-separable sub-graph. It requires deletion of two vertices to disconnect it. Actors that are in more than one bi-component are defined cut-points as their deletion disconnects the graph. The number of bi-components and cut-points provider another indication of the connectivity of a graph. The higher the number, the higher the probability that a graph will be disconnected for the deletion of a vertex, that is for the exit of a player. The size of the bi-components, similarly to the analysis of *k*-cores, gives an indication of the size of highly connected sub-groups. Precisely, bi-components with more than two actors correspond to *k*-cores with *k* greater than 1[2].

4.1 Networks in turboprop and jet industries

Table 1 summarises some network measures at the group and sub-group level for turboprop and jet industries. The measures computed are number of actors (*actors*), level of relational density of the network (*density*), number of *k*-cores with *k*=1 (*1-core*), number of *k*-cores with *k*=2 (*2-core*), number of vertices in the core with k=2 (*2-core size*), number of bi-components (*bi-comp*), number of actors presents in more than one bi-component (*cutpoints*).

At the aggregate level, we observe that the level of density in the jet is higher than in the turboprop, which indicates higher relational intensity among buyer and suppliers. The analysis at the sub-graph level provides details on the distribution of relations across sub-groups of actors. In particular, it gives evidence of the degree of partition and hierarchisation of the network.

The degree of partition of the network in the jet is lower than in the turboprop as the number of *k*-cores with degree equal to 1 is lower in the jet. In the turboprop network the number of *1*-cores increases over time and ranges between 3 and 6 for a large portion of the time, although it tends to decrease over the last years of the industry evolution. In the jet, the network can be sub-divided only in 1 or 2 sub-graphs over all its life, except in the last three years, in which there are three *1*-cores.

The number of 2-cores denotes the degree of hierarchisation of the network. The network of the jet assumes a *hierarchical* configuration as it is possible to identify a cohesive core in which the actors have degree greater than or equal to 2. The core emerged during the first stage of the industry life and was initially composed of 4 actors. The entry of new actors at the end of the 1960s and at the beginning of the 1970s destabilised the network and the core. The intensification of the relational activities of entrants and incumbents led again to the emergence of a core which expanded during the industry evolution. In fact, as evident from the table, the number of actors grew from 4 in 1975 to 8 in 1997, therefore a larger part of actors entered the core. The core was composed of the incumbent engine suppliers and of major aircraft manufacturers operating in multiple sourcing. On the other hand, a periphery was also created in the network, which was composed of actors with degree equal to 1, that is aircraft manufacturers in multiple sourcing and engine suppliers in the regional market. The network was also partitioned in the last three years, as there were three subgroups, two of them in the regional market (Allison-Embraer and Textron-British Aerospace), and the other containing the *2*-core.

The network in the turboprop presents a very different structural dynamics. In fact, except for a five-year period, there are no highly connected sub-groups of actors, as indicated by the absence of *2*-cores in almost all the industry life. Only from 1991 to 1995 a 2-core was formed by four actors, but it was transitory. This indicates that relations among actors are exclusive and sparse, and are not concentrated around a group of actors.

Further evidence on the degree of connectivity of the networks are given by the number of bi-components and cut-points. In the jet, these two variables increase until the beginning of the 1970s, when the network is destabilised by the entry of new actors. Subsequently, the

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[2] Measures of *k*-cores and bi-components are computed by using the software Ucinet 5 (Borgatti et al., 1999).

indicators decrease until 1997, suggesting higher connectivity of the network. In the turboprop, both the number of bi-components and cut-points increase over time, denoting lower connectivity and higher separability of the graph. The difference of the values in jet and turboprop is not very large, especially if compared with the number of actors, which is larger in the latter. This reflects the presence of turboprop engine suppliers, namely Rolls Royce and Pratt & Whitney, which are present in a high number of bi-components. Precisely during the 1970s the number of cut-points is very low, compared to the number of bi-components, because many aircraft manufacturers in single sourcing are supplied by only two engine companies. During the 1980s and 1990s, although the number of bi-components in which Pratt & Whitney is active is still high, the number of cut-points increases, denoting the increasing separability of the network through other nodes.

Combining these results, we observe a *partitioned structure* of the turboprop network and a *hierarchical structure* of the jet network. This difference can be explained by observing the level of segmentation of both upstream and downstream industries, the degree of complementarity of technologies, ant the type of sourcing strategy adopted by aircraft manufacturers.

In the turboprop the high level of market segmentation induces a partitioned network. Most turboprop engine and aircraft manufacturers are specialised by seat-segment. They are mainly active in only one segment of the market, except the leader of the supplier industry, which gradually enters three segments. However, the leader competes fiercely in each segment with minor companies serving a single segment. The low level of economies of scale and scope supports this configuration.

In the jet industry, on the contrary, all major players operate in most segments of the industry, except the companies serving the regional market. On the supply side the presence of economies of scale and scope, reflected in the presence of robust designs of engines which power many aircraft configurations, supports a configuration of interdependence of sub-markets. However, by 1998 firms in both the engine and aircraft large commercial sector, active in the core identified, have been entering the small jet segment of the market, which will lead to higher connectivity of the network.

As we noted earlier, the turboprop network is characterised by the presence of buyers' single sourcing, which is also quite stable over the lifetime of firms. A number of companies started to operate in dual sourcing, but they continued to power their aircraft programs with engines by a single supplier. Very often, dual sourcing is adopted when programs are introduced in different segments of the markets. Therefore, the diffusion of single sourcing at the firm, at the segment and at the program level induces a partitioned network.

Differently in the jet the shift from single and dual toward multiple sourcing strategies of major aircraft manufacturers led to the formation of cohesive network structures.

In summary, in the jet industry a hierarchical structure of the network emerges and stabilises over the course of industry evolution, while in the prop it is not possible to identify a core. Relations are almost equally distributed among buyers and suppliers, except for the leader in the supplier industry which, however, changes during the industry evolution. The density in the turboprop network is therefore lower than in the jet industry.

An implication for the interpretation of the network as a transmission mechanism of changes from a downstream to an upstream industry is that a hierarchical network *filters* the transmission of effects, while a partitioned network transmits *directly* the effects.

Table 1. Density, *k*-cores and bi-components in turboprop and jet networks

	TURBOPROP							**JET**						
	actors	*density*	*1-core*	*2-core*	*size 2-core*	*bi-comp*	*cut-points*	*actors*	*density*	*1-core*	*2-core*	*size 2-core*	*bi-comp*	*cut-points*
1953	2	1,00	1	-	-	1	0							
1954	2	0,50	1	-	-	1	0							
1955	5	1,00	2	-	-	3	1							
1956	6	0,50	1	-	-	2	1							
1957	7	0,50	2	-	-	3	1							
1958	8	0,50	2	-	-	5	1	4	0,50	2	-	-	2	0
1959	8	0,50	2	-	-	5	1	6	0,50	2	-	-	4	2
1960	8	0,50	2	-	-	5	2	7	0,47	2	1	4	4	1
1961	8	0,58	2	-	-	6	2	7	0,47	2	1	4	4	1
1962	9	0,33	2	-	-	7	2	7	0,47	2	1	5	3	1
1963	11	0,38	3	-	-	8	2	9	0,43	2	1	4	6	1
1964	10	0,25	2	-	-	8	3	9	0,42	2	1	4	7	2
1965	13	0,31	3	-	-	10	4	9	0,43	2	1	4	6	2
1966	13	0,29	2	-	-	10	5	8	0,67	1	1	4	5	2
1967	13	0,28	2	-	-	10	5	10	0,48	1	1	4	7	3
1968	13	0,26	2	-	-	11	4	10	0,50	1	1	4	6	3
1969	12	0,30	3	-	-	9	2	10	0,43	1	-	-	9	4
1970	10	0,29	3	-	-	6	2	11	0,37	1	-	-	10	4
1971	10	0,23	3	-	-	7	3	11	0,38	2	-	-	8	3
1972	13	0,25	4	-	-	9	2	13	0,36	2	-	-	10	4
1973	13	0,25	4	-	-	7	2	14	0,38	2	-	-	9	4
1974	15	0,20	4	-	-	8	2	14	0,38	2	-	-	9	2
1975	15	0,21	5	-	-	9	2	14	0,38	2	1	4	9	2
1976	14	0,16	4	-	-	10	4	13	0,42	2	1	4	7	3
1977	16	0,23	6	-	-	11	3	13	0,46	1	1	6	7	3
1978	14	0,23	4	-	-	8	3	13	0,43	1	1	4	9	2
1979	13	0,29	4	-	-	8	3	11	0,51	1	1	4	6	3
1980	13	0,28	3	-	-	7	3	11	0,52	1	1	5	7	2
1981	14	0,24	3	-	-	9	4	12	0,44	1	1	5	6	3
1982	16	0,22	3	-	-	12	5	13	0,41	1	1	5	8	3
1983	17	0,16	4	-	-	11	4	13	0,35	2	1	4	8	3
1984	21	0,21	5	-	-	12	5	13	0,44	1	1	5	7	3
1985	21	0,22	3	-	-	12	7	13	0,36	2	1	5	8	3
1986	21	0,27	2	-	-	12	7	13	0,35	2	1	4	8	3
1987	21	0,22	1	-	-	12	7	12	0,44	2	1	6	5	2
1988	21	0,21	2	-	-	12	7	12	0,49	2	1	6	4	2
1989	19	0,21	3	-	-	12	6	13	0,49	2	1	6	5	3
1990	19	0,24	3	-	-	12	6	13	0,44	2	1	6	6	3
1991	20	0,22	2	1	4	12	6	12	0,49	2	1	6	5	3
1992	19	0,34	3	1	4	12	5	13	0,44	2	1	6	6	4
1993	18	0,34	1	1	4	12	5	13	0,44	2	1	6	6	4
1994	18	0,27	1	1	4	12	5	13	0,44	2	1	6	6	4
1995	18	0,25	2	1	4	12	6	14	0,39	3	1	8	5	2
1996	16	0,33	2	-	-	12	7	14	0,39	3	1	8	5	2
1997	16	0,33	1	-	-	12	7	14	0,39	3	1	8	5	2

5. Observing the transmission mechanism

The comparison between the two pairs of industries shows an intriguing difference. In the turboprop industry, the dynamics of the upstream industry closely parallel the dynamics of the downstream one. The turboprop aircraft industry exhibits a remarkable increase in the number of firms, a rapidly decreasing and then stable level of concentration, and an increasing number of products, with some oscillations. Almost the same patterns of change apply to the related engine industry.

This is not true for the jet. In the aircraft industry the number of firms is almost stable, concentration is slightly decreasing and the number of products has a peak and then declines. By contrast, a different pattern is found in the engine industry: the number of firms is always increasing, concentration is sharply decreasing, and the number of products has an increasing trend.

To test this effect a simple correlation coefficient was computed between the time series describing the four variables in the two pairs of vertically-related industries. Results are shown in Table 2. They indicate that the Pearson correlation coefficient is much higher in the turboprop than in the jet for all variables.

Table 2. Correlation coefficients in turboprop and jet markets

		TURBOPROP	**JET**
Number of firms	Pearson correlation coefficient	0.903**	0.474**
	significance level	0.000	0.002
	no. of observations	49	40
Concentration	Pearson correlation coefficient	0.889**	0.628**
	significance level	0.000	0.000
	no. of observations	49	40
Number of products	Pearson correlation coefficient	0.961**	0.485**
	significance level	0.000	0.002
	no. of observations	49	40
Number of new products	Pearson correlation coefficient	0.739**	0.225
	significance level	0.000	0.162
	no. of observations	49	40

** Correlation is significant at the 0,01 level

How can this difference be explained?

As shown in section 4, the network linking the two industries assumes a sharply different configuration in the two cases. We argue that networks matter. The partitioned network more directly transmits the effects to the upstream industry, while the hierarchical network filters the effects.

In the turboprop industry, every change on the buyer side directly impacts on the supplier side. With respect to the number of firms, we observed that the entry of suppliers always follows the entry of an aircraft manufacturer. In a context characterised by stability of relations, high costs of switching suppliers, and preference toward single sourcing, the opportunities for entry come from the entry of a new unattached buyer and much less frequently from the introduction of a new program. Similarly, in such a fragmented market the exit of a customer means the disappearance of the market for the supplier, which is therefore forced to exit the industry. In fact, the interruption of relations due to exit of aircraft manufacturers represents a loss of market shares that cannot be compensated by acquisition of supply relations with existing customers, already attached to competing suppliers in single sourcing.

This explains the strongly related dynamics of entry, exit and number of players in the turboprop aircraft and engine industries.

On the contrary in the jet industry, the entry of jet aircraft manufacturers may produce opportunities for entry of engine suppliers only indirectly through the growth of the market. The opportunities for entry are instead created by the shift from single to dual and multiple sourcing of aircraft manufacturers, which contributes to create a cohesive and hierarchical structure of the network. The openness of the network structure, that is the reachability of central nodes of the network, reduces the barriers to entry of new suppliers, which may enter for supplying existing and already attached buyers.

With respect to the level of concentration, in the turboprop industry, although the levels of concentration upstream and downstream are very different, their dynamics are highly correlated, as exhibited by the value of the Pearson correlation coefficient. Again the partitioned structure of the network, mirroring an extremely fragmented market structure in which the customer may represent the market of only one supplier, transmits directly the effects of changes in market shares and, therefore, in the level of downstream concentration to the upstream industry. In other words, a decrease or an increase of the market share of a customer, or the exit or entry of a customer, cause an increasing or decreasing concentration, respectively. In a fragmented structure, this change impacts on the market share of only one supplier, and induces a change in the level of upstream concentration of the same direction and intensity.

The correlation coefficients of total number of products, and number of new products in the aircraft and engine industries confirm even more sharply the previous results. In the jet industry there is a low correlation for the first indicator and a non significant correlation for the second, while in the turboprop the coefficient is very high for both measures. In the prop, the technological co-specialisation of engine and aircraft, which is also reflected in the high number of bi-components and of *k*-cores with minimum degree equal to 1, explains the entry of isolated couples of vertically-related firms and products. This means that new engines are realised for specific new aircraft and are very rarely used for other applications.

On the other side, a new aircraft is designed to integrate a specific engine. Therefore, the dynamics of the number of products is highly related.

In the jet industry this relation is quite weak (number of products) or it is non significant (introduction of new products). This is explained by several factors. The presence of economies of scale and scope in the engine production may imply the use of the same engine for aircraft in different market segments (constant or decreasing number of engines and increasing number of new aircraft); multiple sourcing at the product level implies that keeping constant the number of aircraft, the number of engines can be increasing. Moreover, engine companies in the core of the network compete in technological solutions by introducing new and more powerful engines for the same aircraft.

In sum, in the turboprop industry the partitioned structure of the network represents a direct transmission mechanism of the changes in upstream and downstream industries. Suppliers cannot resist pressures from the customer industry, because they do not have access to the entire customer base, but to a small number of airframe manufacturers. Their destiny is entirely linked to the evolution of the downstream industry.

By contrast, in the jet engine industry the hierarchical structure of the network, with a core and a periphery, filters the impulse provided by the structural changes of demand, and prevents the shakeout, the emergence of the leader and the increase in concentration.

6. Conclusions and further research

The main message of the paper is that networks matter in the explanation of the evolution of industries. Depending on technology and market factors, networks of vertical relations assume a variety of structural configurations and change over time. Once formed, networks evolve themselves and act as constraints to the evolution of industries, transmitting effects from related industries according to their configuration.

We showed through a quasi laboratory case that specific characteristics of the industries, which refer to technological factors, market segmentation and buyers’ sourcing strategies, are reflected in *partitioned* network structures in the turboprop and in *hierarchical* network structures in the jet.

The correlation between industrial dynamics in downstream and upstream industries, measured in terms of number of firms, industrial concentration, number of products and introduction of new products, is much higher in the turboprop than in the jet. We propose that partitioned network structures *transmit directly* the changes of downstream to upstream industries, while hierarchical networks *filter* the effects.

The analysis developed in this paper will be applied in different industrial contexts. Further research will aim to study the relations between airline companies and aircraft manufacturers. Two important factors may have affected the sourcing of airlines: the role of commonality across different engines and aircraft, which allows important cost savings for airlines, and the trend toward outsourcing of maintenance activities, which reduces the cost savings of having a single supplier. The analysis of the vertical relations between engine, aircraft and airline industries will offer different cases characterised by different structures of upstream and downstream industries. While in this paper we analysed *small-number buyer and supplier industries*, the analysis of the airline industry will remove this restriction on the downstream side, as the industry is composed of hundreds of companies and is characterised by very turbulent dynamics, also fuelled by the deregulation process that has occurred in the United States and in Europe. Again, the comparison between markets for jet and turboprop aircraft will allow further specifications of market structures and of demand regimes, as the development of air carriers in the markets for turboprop and jet followed differentiated dynamics.

A further development of this work will have as its object of analysis the dynamics of the network of vertical relations between avionics and aircraft manufacturers. In that case we will extend the application of the theory to a *supplier industry* characterised by the presence of a *large number of firms*. The avionics industry is also composed of a number of market segments characterised by different technologies which witnessed strong changes in the last few decades.

The analysis of the network in different industrial contexts will provide cases which will enrich and enlarge the general applicability of the proposed approach.

Appendix. Data

Empirical analysis is carried out in the turboprop and jet aircraft-engine industries since their birth to 1997, by using a *proprietary database* built upon several sources of data.

Specifically, we use the *Atlas Aviation* and *Jane's All the World Aircraft* databases, IATA publications, technical press and literature on the history and technological development of the aviation industry[3]. The *Atlas Aviation Database* contains all the transactions occurring from 1948 to 1997 between aircraft manufacturers and airline companies (orders) in the market for large commercial aircraft. The data distinguish the engine technology adopted, jet and turboprop, and for each transaction it is possible to identify the engine model integrated into the aircraft ordered. The jet industry includes all turbojet and turbofan engines, from the first Pratt & Whitney JT3 introduced in 1958. The turboprop includes all turbine propeller engines from the Rolls Royce Conway in the Vickers Viscount in 1948.

The database provides data on more than 85,000 transactions, carried out by 5,900 operators, 27 aircraft companies and 11 engine manufacturers, and involving 102 aircraft models (more than 450 versions) and 260 engine types. For each transaction the database provide three monthly dates: contract, first flight (also indicated as production date), and delivery. We use the first flight as unit of analysis as it is subject to less fluctuation. To reduce discontinuity in the data, monthly dates are transformed into annual dates. Data on three aircraft programs not included in Atlas have been added by using Aerospatiale (1990) data on orders and deliveries.

Transactions include also second-hand transfers between operators. As we are interested in the relations between engine and aircraft manufacturers, we consider only the first introduction of the product and do not consider each subsequent transaction occurring between airline companies. The final number of transactions used in the analysis is 27,000.

We integrated the *Atlas* database with data on the number of engines powering each aircraft, by using other sources: *Jane's All the World Aircraft* publications and the technical press (in particular, *Flight International* and *Aviation Week and Space Technology*). Data on seat capacity of aircraft, and information about segmentation by seat are provided by company reports (in particular Boeing, Airbus, Aerospatiale).

Russian aircraft and engine transactions are excluded from this analysis, because of some incompleteness and uncertainty about data in the version of the database used for this research. This is not a problem with respect to the objectives of this thesis, since historically Russian engines have been exclusively integrated into aeroplanes produced in Russia, thus the relational dynamics in the engine industry of the rest of the world are not influenced very much.

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[3] Among others, Miller and Sawers, 1968; Phillips, 1971; Klein, 1977; Constant, 1980; Bluestone et al., 1981; Bright, 1981; Mowery and Rosenberg, 1982, 1989; Hayward, 1986, 1994; Vincenti, 1990; World Aerospace Technology, 1993; Norris and Wagner, 1997; Sutton, 1998.

Entry is defined as the first date an engine manufacturer supplies an engine to an aircraft manufacturer (indicated by the date of production). A firm experiences exit when it does not supply engines for at least 5 consecutive years. Entry and exit of companies are analysed simply by counting the number of companies in the engine industry and their life cycle. The calculation of rates of entry and exit is not significant given the small number of players.

Data on which concentration measures are computed are based on total sales of commercial aircraft manufacturers over the entire period of observation, expressed in physical quantities (orders). To take into consideration sales of aero-engine firms, aircraft orders are multiplied by the number of engines installed in the model, as described in the technical literature. No consideration is given to the spare units sold in the maintenance and repair market. Market shares are therefore defined in terms of quantities rather than turnover, since there is no such detailed information available at the level of individual aircraft and engine programs.

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